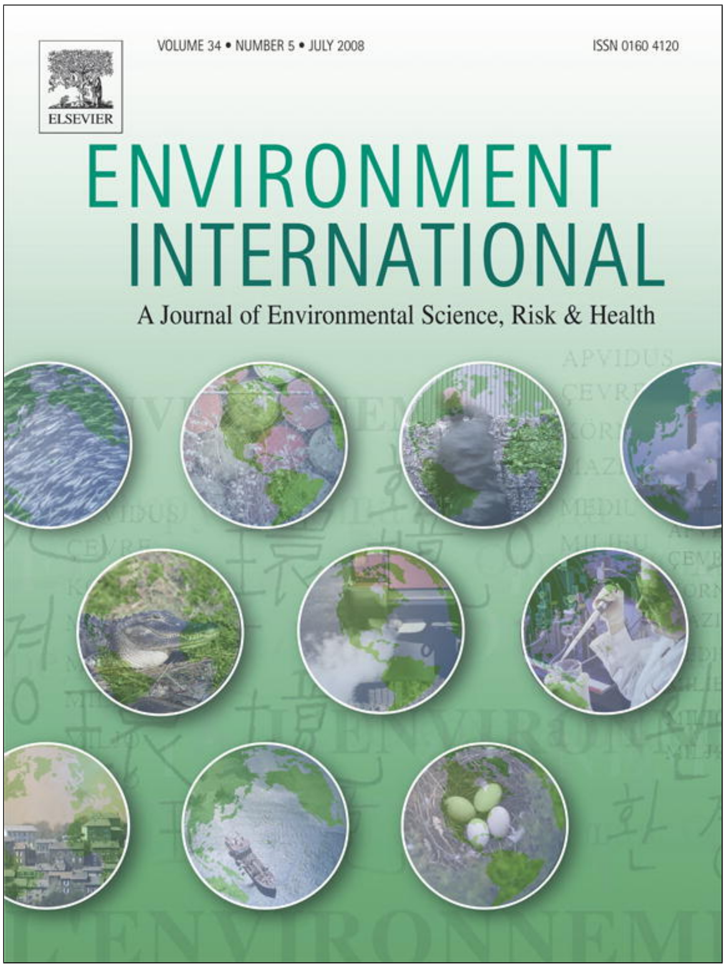
VOLUME 34 • NUMBER 5 • JULY 2008
ISSN 0160 4120
ELSEVIER
ENVIRONMENT INTERNATIONAL
A Journal of Environmental Science, Risk & Health

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Particulate air pollution in Lanzhou China**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Naval Ocean-Atmospheric Prediction (NOAP) Laboratory,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Concentrations of total suspended particles (TSP) and PM10 in Lanzhou China have been kept high for the past two decades. Data collected during the intensive observational period from October 1999 to April 2001 show high TSP and PM10 concentrations. Starting from November, the PM10 pollution intensifies, and reaches mid to high alert level of air pollution, continues until April next year, and is at low alert level in the summer. In the winter and spring, the TSP concentration is 2?10 times higher than the third-level criterion of air quality (severe pollution). Effects of intrinsic factors (sources of pollution) and remote preconditions (propagation of dust storms) for severe PM10 and TSP pollution in Lanzhou are analyzed.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

Available online at www.sciencedirect.com

ScienceDirect

Environment International 34 (2008) 698–713

ENVIRONMENT INTERNATIONAL

www.elsevier.com/locate/envint

Particulate air pollution in Lanzhou China

Peter C. Chu [a,*], Yuchun Chen [b], Shihua Lu [b], Zhenchao Li [b], Yaqiong Lu [c]

[a] *Naval Ocean-Atmospheric Prediction (NOAP) Laboratory, Naval Postgraduate School Monterey, California, USA*
[b] *Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China*
[c] *Department of Atmospheric Science, Chengdu University Of Information Technology, Chengdu, China*

Available online 29 January 2008

Abstract

Concentrations of total suspended particles (TSP) and PM_{10} in Lanzhou China have been kept high for the past two decades. Data collected during the intensive observational period from October 1999 to April 2001 show high TSP and PM_{10} concentrations. Starting from November, the PM_{10} pollution intensifies, and reaches mid to high alert level of air pollution, continues until April next year, and is at low alert level in the summer. In the winter and spring, the TSP concentration is 2–10 times higher than the third-level criterion of air quality (severe pollution). Effects of intrinsic factors (sources of pollution) and remote preconditions (propagation of dust storms) for severe PM_{10} and TSP pollution in Lanzhou are analyzed.

Keywords: Particulate pollutants; Dust storm; Air quality; Air pollution index; TSP; PM_{10}

1. Introduction

Lanzhou is located at a narrow (2–8 km width), long (40-km), NW–SE oriented valley basin (elevation: 1500-m to 1600-m) with the Tibetan plateau in the west, Baita mountain (above 1700-m elevation) in the north, and the Gaolan mountain (above 1900-m elevation) in the south (Fig. 1a). The Yellow River runs through the city from the west to the east. Lanzhou has four districts (Fig. 1b): Chengguan, Qilihe, Xigu, and Anning. Chengguan (District-I), located in the eastern valley, is the metropolitan area including government, commerce, culture, and residence. Xigu (District-III), located in the western valley, is the large heavy industrial area. Qilihe (District-II), located in the middle valley, and Anning (District-IV), located in the north middle valley, are the mixed residential, small factories, and farming (vegetables) area.

The topographic characteristics make Lanzhou vulnerable to the particulate pollution (Fig. 1b). The aspect ratio of the valley (depth versus width) is around 0.07, which blocks the air streams due to large frictional forces and causes weak winds and stable stratification (even inversion) inhibiting turbulent diffusion. The meteorological conditions (low winds, stable stratification especially inversion) cause the pollutants difficult to disperse. These conditions make Lanzhou one of the most polluted cities in China (Fig. 1c).

Local sources and remote preconditions cause the particulate pollution in Lanzhou. The major local sources are fossil-fuel combustion (which produces ash and soot), industrial processes (involving metals, fibers, etc.), transportation, wind and soil erosion (producing fugitive dust), and photochemical reactions (complex chain reactions between sunlight and gaseous pollutants). The remote preconditions are usually dust storms frequently occurring in nearby deserts and surrounding areas (Prospero et al., 2002). Dust storms occurring over Northwest China may extend to North Pacific, Japan and Korea (Duce et al., 1980). Particularly severe dust storms can even go across the Pacific and reach the Western Coast of North America as was the case for the April 18, 1998, dust storm (Wang et al., 2003).

* Corresponding author. Tel.: +1 831 656 3688; fax: +1 831 656 3686.
E-mail address: pcchu@nps.edu (P.C. Chu).
URL: http://www.oc.nps.navy.mil/~chu (P.C. Chu).

0160-4120/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envint.2007.12.013

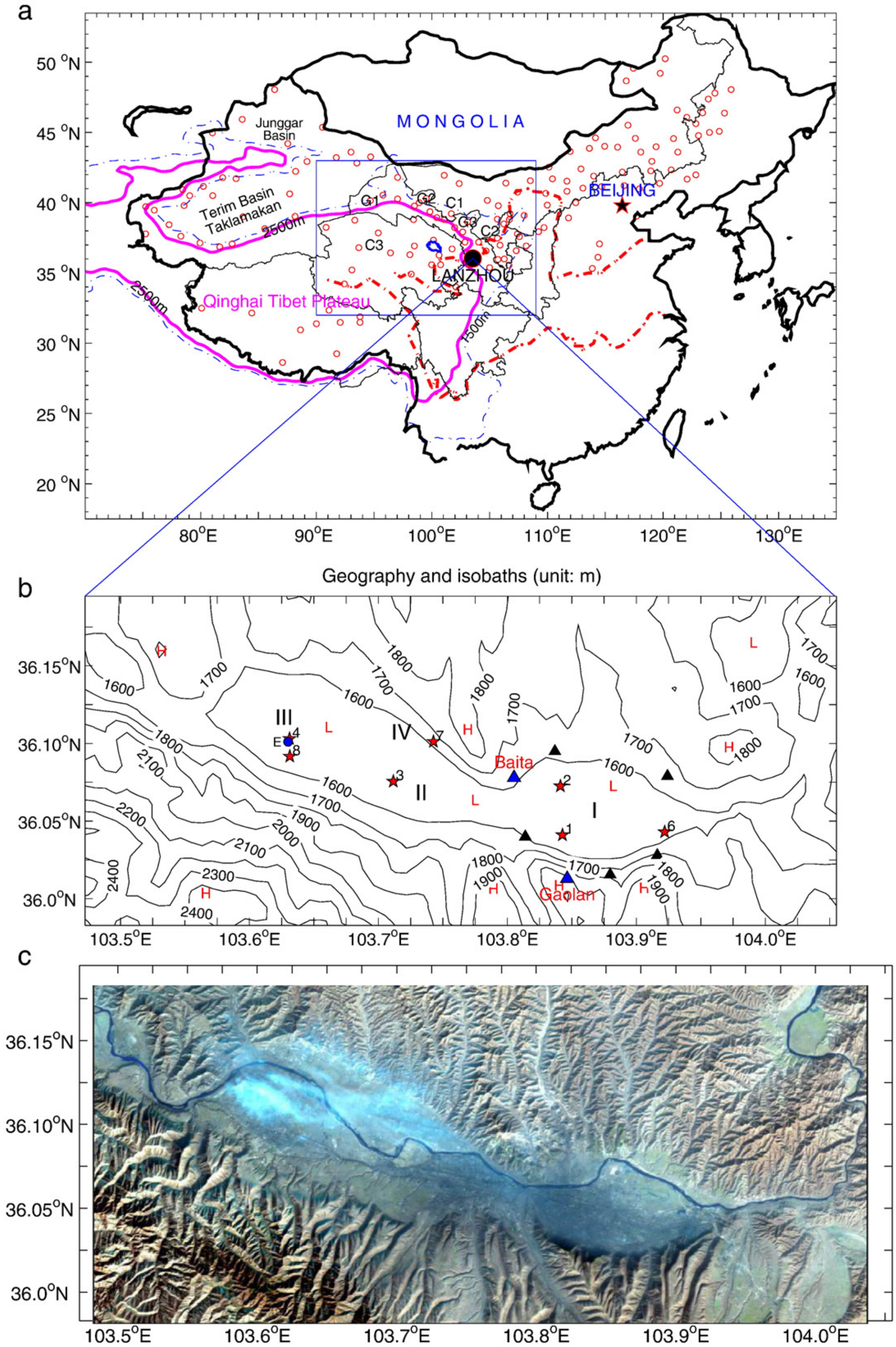

Fig. 1. Lanzhou: (a) geography, (b) topography, and (c) LANDSAT-TM imagery representing air pollution on 3 January 2001.

Environmental Protection Agency of China (EPA-China) set up air quality standard focusing on total suspended particles (TSP) and smaller particles that are likely responsible for adverse health effects because of their ability to reach the lower regions of respiratory tract. The PM_{10} standard includes particles with a diameter of 10 µm or less (one-seventh the

Table 1
Air quality standards for annual mean particulate pollutant concentrations (mg m^{-3}) from the Chinese National Environmental Protection Agency

Level of criterion	TSP	PM_{10}
1	0.08	0.04
2	0.2	0.10
3	0.3	0.15

width of a human hair). EPA-China's health-based national air quality standard for (TSP, PM_{10}) is (0.08, 0.04) mg m^{-3} (measured as an annual mean) (Table 1) and (0.12, 0.05) mg m^{-3} (measured as a daily concentration) (Table 2). Major concerns for human health from exposure to PM_{10} include: effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. The elderly, children, and people with chronic lung disease, influenza, or asthma, are especially sensitive to the effects of particulate matter. The second-level and third-level air pollution criteria for annual mean (TSP, PM_{10}) are (0.2, 0.10 mg m^{-3}), (0.3, 0.15 mg m^{-3}) (Table 1). The second-level and third-level criteria for daily mean (TSP, PM_{10}) are (0.3, 0.15 mg m^{-3}), (0.5, 0.25 mg m^{-3}) (Table 2). In Lanzhou, EPA-China alerts the commercial and residential regions as the pollutants reach the second-level criteria and alerts the industrial regions as the pollutants reach the third-level criteria.

In this study, the particulate air pollution in Lanzhou is investigated through intensive measurements of (TSP, PM_{10}) during October 1999 to April 2001 by the air quality monitoring system as well as the associated meteorological observations. Fig. 1b shows location of nine sampling stations with St-1 to St-8 measuring TSP concentration and St-E measuring PM_{10} concentration. The objectives are to detect detailed temporal and spatial variability of TSP and PM_{10}, to evaluate the air quality objectively and quantitatively, to analyze the pollutant sources, and to find the favorable meteorological conditions for the pollutant dispersion. Comparison between observed (TSP, PM_{10}) concentrations and EPA-China criteria gives the level of the particulate pollution. Comparison between observed (TSP, PM_{10}) concentrations and the meteorological conditions may provide the cause of the particulate pollution. The rest of the paper is outlined as follows. Sections 2 and 3 show the temporal and spatial variability of (TSP, PM_{10}) concentrations and associated air pollution indices. Section 4 shows the statistical analysis.

Table 2
Air quality standards for daily mean particulate pollutant concentrations (mg m^{-3}) from the Chinese National Environmental Protection Agency

Level of criterion	TSP	PM_{10}
1	0.12	0.05
2	0.3	0.15
3	0.5	0.25

Table 3
Location of observational stations and total temporally mean TSP concentrations (mg m^{-3})

Site	Longitude E	Latitude N	Height above surface (m)	Region	TSP
St-1	103.84	36.04	25	Chengguan (District-1)	0.69
St-2	103.84	36.07	11	Chengguan (District-1)	0.57
St-3	103.71	36.08	15	Qilihe (District-3)	0.74
St-4	103.63	36.10	22	Xigu (District-2)	0.68
St-5	104.09	35.84	4	Yuzhong County	0.28
St-6	103.92	36.04	19	Chengguan (District-1)	0.56
St-7	103.74	36.10	15	Anning (District-4)	0.52
St-8	103.63	36.09	4	Xigu (District-2)	0.54

Note that the second-level annual mean criterion of TSP concentration is 0.20 mg m^{-3}.

Section 5 discusses the possible causes for the particulate pollution. Section 6 presents the conclusions.

2. Pollutant concentration

An air quality monitoring system has been established in Lanzhou with multiple sampling at each station (Fig. 1a). This is the part of the project entitled Air Pollution and Control in Lanzhou (APCL), supported jointly by Gansu Province and the Chinese Academy of Sciences and carried out from 1999 to 2001 (Chu et al., 2004, 2008). At each station, TSP is measured using a high-volume air sampler that draws a large known volume of air through a pre-weighed filter for 24 h. After sampling, the filter is re-weighed and the difference in filter weight is the particulate mass. The concentration of TSP (mg m^{-3}) in the air is calculated as the particulate mass divided by the volume of air sampled. PM_{10} is directly and continuously measured by the real time particulate monitor, Tapered Element Oscillating Microbalance (TEOM) 1400A, which collects the mass on a filter and provides continuous particulate concentration data (mg m^{-3}).

The data are from several sources: the APCL project, routine air quality observations, and routine meteorological observations. From the APCL project, the air quality data were collected at observational stations (St-1 to St-5) from October 1999 to April 2001 and at observational stations (St-6 to St-8) from August 2000 to April 2001. The station-5 (Yuzhong), located in countryside, is taken as the reference station (Fig. 1b). Over these stations, daily TSP concentration is calculated.

The total temporally mean TSP concentration exceeds the third-level annual mean TSP concentration criterion (0.3 mg m^{-3}) for all stations except for the background station (St-5: 0.28 mg m^{-3}) (Table 3). Among them, (St-1, St-3, St-4) have (0.69, 0.74, 0.68) mg m^{-3}, which are twice larger than the third-level annual mean standard (0.3 mg m^{-3}). Even at the reference station (St-5), the annual mean TSP concentration (0.28 mg m^{-3}) is quite close to the third-level national criterion (0.30 mg m^{-3}) (comparison between Tables 3 and 1).

The daily PM_{10} concentration was collected continuously from the routine air quality observations by EPA-China in Lanzhou from June 2000 to May 2001 (station-E in Fig. 1b).

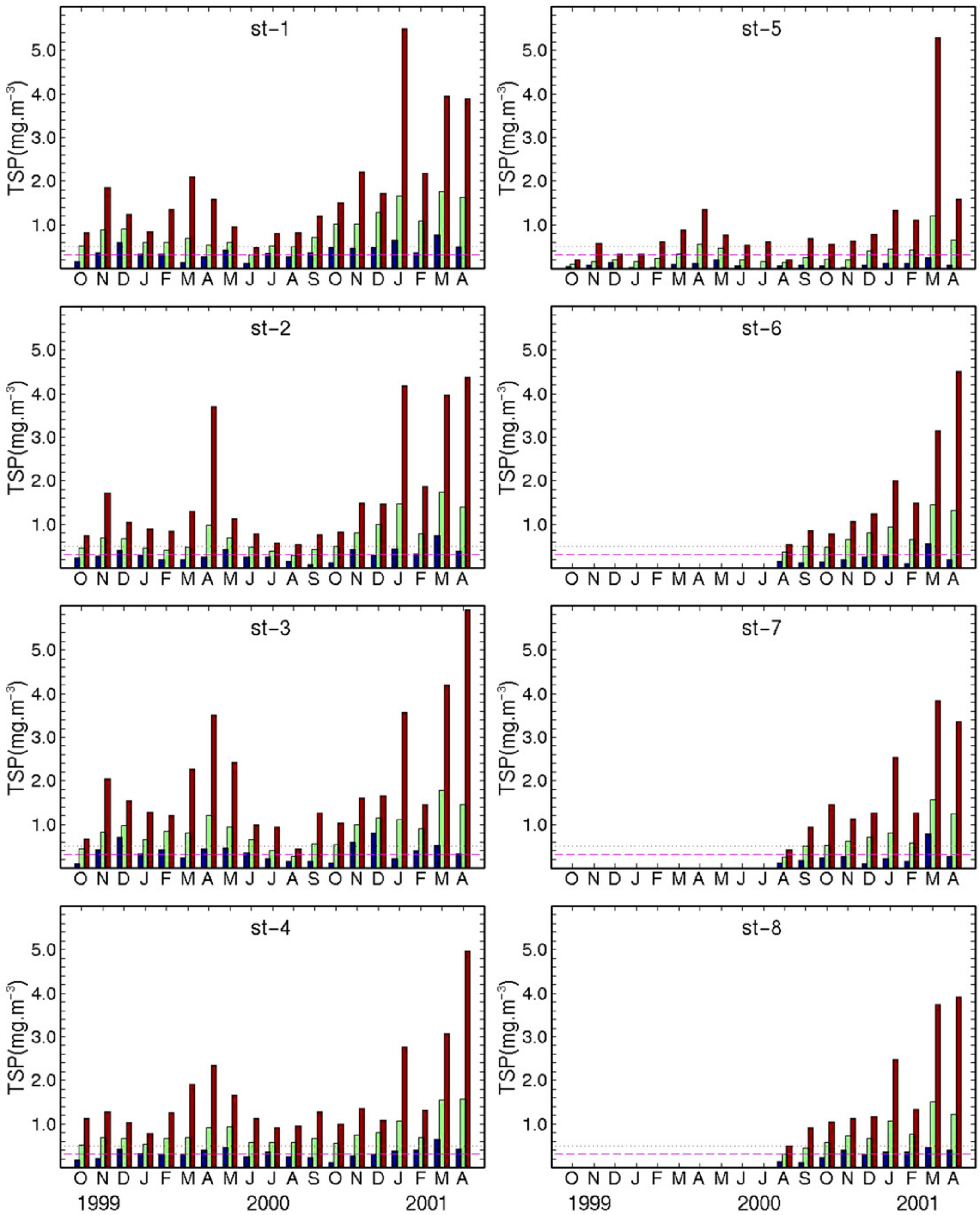

Fig. 2. Monthly mean, maximum, and minimum TSP concentrations (mg m^{-3}) at St-1 to St-8.

Fig. 2 shows the monthly mean, minimum, and maximum TSP concentration (mg m^{-3}) at the eight stations. The horizontal dashed and solid lines are referred to as the second and third-level criterions for daily mean concentrations (Table 2). The monthly mean TSP concentration exceeds the second-level daily mean TSP standard (0.3 mg m^{-3}) all the time at all the stations in the urban area of Lanzhou. Even in the reference station (St-5) located in the countryside, the monthly mean TSP concentration often exceeds the second-level daily mean TSP criterion. The monthly maximum TSP concentration in the reference station (St-5) always exceeds the second-level daily mean TSP criterion and even exceeds the third-level daily mean TSP criterion (1.0 mg m^{-3}) quite often. At the seven urban stations, the monthly maximum TSP concentration often exceeds the third-level daily mean TSP criterion.

Taking March 2001 as an example, the monthly mean TSP concentration is 4–6 times larger than the monthly mean third-level criterion (0.3 mg m^{-3}). Even in the reference station (St-5), the observed monthly mean TSP concentration is 1.21 mg m^{-3}, which is more than 4 times of the third-level criterion (Table 4). The monthly maximum TSP concentration is more than six times higher than the daily mean third-level criterion

Table 4
TSP and PM_{10} concentration (mg m^{-3}) in March 2001

	St-1 TSP	St-2 TSP	St-3 TSP	St-4 TSP	St-5 TSP	St-6 TSP	St-7 TSP	St-8 TSP	St-E PM_{10}
Max	3.96	3.98	4.21	3.08	5.29	3.15	3.84	3.75	1.12
Min	0.77	0.74	0.51	0.64	0.25	0.55	0.79	0.46	0.19
Mean	1.76	1.74	1.77	1.55	1.21	1.45	1.57	1.51	0.39

Table 5
Monthly mean and maximum PM_{10} concentrations (mg m^{-3}) from June 2000 to May 2001

Month	6	7	8	9	10	11	12	1	2	3	4	5
Mean	0.20	0.17	0.15	0.15	0.20	0.30	0.35	0.49	0.32	0.39	0.45	0.18
Max	0.89	0.57	0.28	0.33	0.34	0.72	0.56	2.56	1.23	1.12	1.54	0.47

Table 6
API and air quality management in China

Air pollution index	Air quality classification		Air quality description and management
API ≤ 50	I	Clean	No action is needed.
50 < API ≤ 100	II	Good	No action is needed.
100 < API ≤ 150	III_1	Low-level pollution	Persons should be careful in outdoor activities.
150 < API ≤ 200	III_2		
200 < API ≤ 250	IV_1	Mid-level pollution	Persons with existing heart or respiratory illnesses are advised to reduce physical exertion and outdoor activities.
250 < API ≤ 300	IV_2		
API ≥ 300	V	High-level pollution	Air pollution is severe; The general public is advised to reduce physical exertion and outdoor activities.

Table 7
Monthly mean, maximum, and minimum API of TSP in March 2001

	St-1 TSP	St-2 TSP	St-3 TSP	St-4 TSP	St-5 TSP	St-6 TSP	St-7 TSP	St-8 TSP
Max	>500	>500	>500	>500	>500	>500	>500	>500
Min	359	346	209	306	87	238	365	365
Mean	>500	>500	>500	>500	400	>500	>500	>500

(0.5 mg m^{-3}) in all the eight stations. The monthly minimum TSP concentration is higher than the daily mean third-level criterion (0.5 mg m^{-3}) in most stations except the reference station (St-5, 0.25 mg m^{-3}) and St-8 (0.46 mg m^{-3}). The monthly mean PM_{10} (0.39 mg m^{-3}) is also much higher than its third-level criterion (0.15 mg m^{-3}). Among the eight stations, five stations (St-1 to St-5) have two years' data. The monthly mean PM_{10} concentration exceeds the second-level criterion all the time (Table 5).

3. Air pollution indies

Air pollution index (API) is a quantitative measure for uniformly reporting the air quality for different constituents and connects to the human health. API is the conversion of the ambient TSP and PM_{10} measured at the sampling stations to a scale of 0 to 500. An index of 100 corresponds to the short-term Air Quality Objective established under the Air Pollution Control Ordinance. EPA-China classifies the air quality standards into 5 major categories due to API values (Table 6): I (clean), II (good), III (low-level pollution), IV (mid-level pollution), and V (high-level pollution). The categories III and IV have two sub-categories: (III_1, III_2) and (IV_1, IV_2). Daily mean APIs of (TSP, PM_{10}) for each station were analyzed to show the spatial and temporal variability of the particulate pollution. Monthly mean, maximum, and minimum APIs (listed in Tables 7 and 8) are computed from the daily mean APIs.

Daily mean API of PM_{10} at St-E (Fig. 3) shows severe PM_{10} pollution during the observational period from June 2000 to May 2001. API for PM_{10} changes drastically and has large values (more than 500) in almost all seasons such as summer (June 13 and July 27, 2000) and winter (December 2000 to January 2001). API for PM_{10} is usually below 200 from August to October 2000. It increases drastically in November 2000, and keeps high values (200–600, categories IV and V) until April, 2001.

Monthly mean API for TSP is large even in the background station (St-5) with the value larger than 200 during April–May 2000 and January–April 2001 (Fig. 4). It is always greater than 200 during the whole observational period at St-4 with a maximum value above 600 in March 2001. At the other stations, it is generally greater than 200 (but always larger than 100) during the period except in summer 2000. March 2001 is one of the severely polluted months of TSP (Table 7). The maximum API for TSP at all eight stations is greater than 500. The monthly mean API of TSP is greater than 500 in all the city stations with 400 in the background station (St-5).

Monthly mean API of PM_{10} is larger than 200 and the maximum API of PM_{10} is larger than 500 during November 2000 to April 2001 (except maximum API = 464 in December 2000) (Table 8). During the other period, the monthly mean API of PM_{10} is equal to or less than 126, but the maximum API of PM_{10} is still large such as greater than 500 in June 2000, 467 in July 2000, and 356 in May 2001. This indicates the intermittent feature of the PM_{10} pollution events.

4. Statistical analysis

Fig. 5 shows the evolution of annual mean TSP concentration measured at the local EPA-China station (103.631°E, 36.103°N), which is marked as the solid circle in Fig. 1b. The annual mean TSP concentration is always above the third-level

Table 8
Monthly mean and maximum API of PM_{10} from June 2000 to May 2001

Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Mean	134	115	102	101	126	206	255	276	210	264	294	118
Max	>500	467	160	192	197	>500	464	>500	>500	>500	>500	356

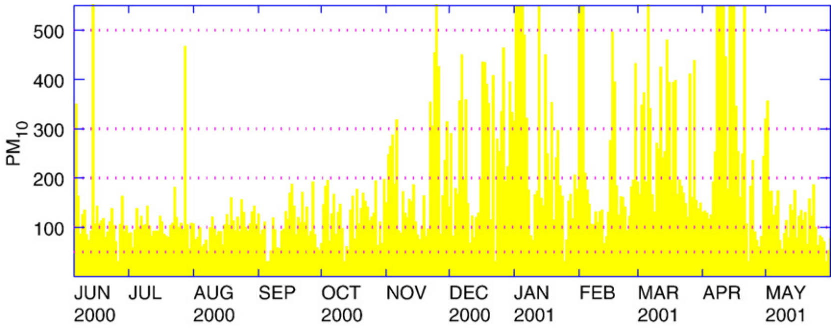

Fig. 3. Daily mean API of PM_{10} at station-E.

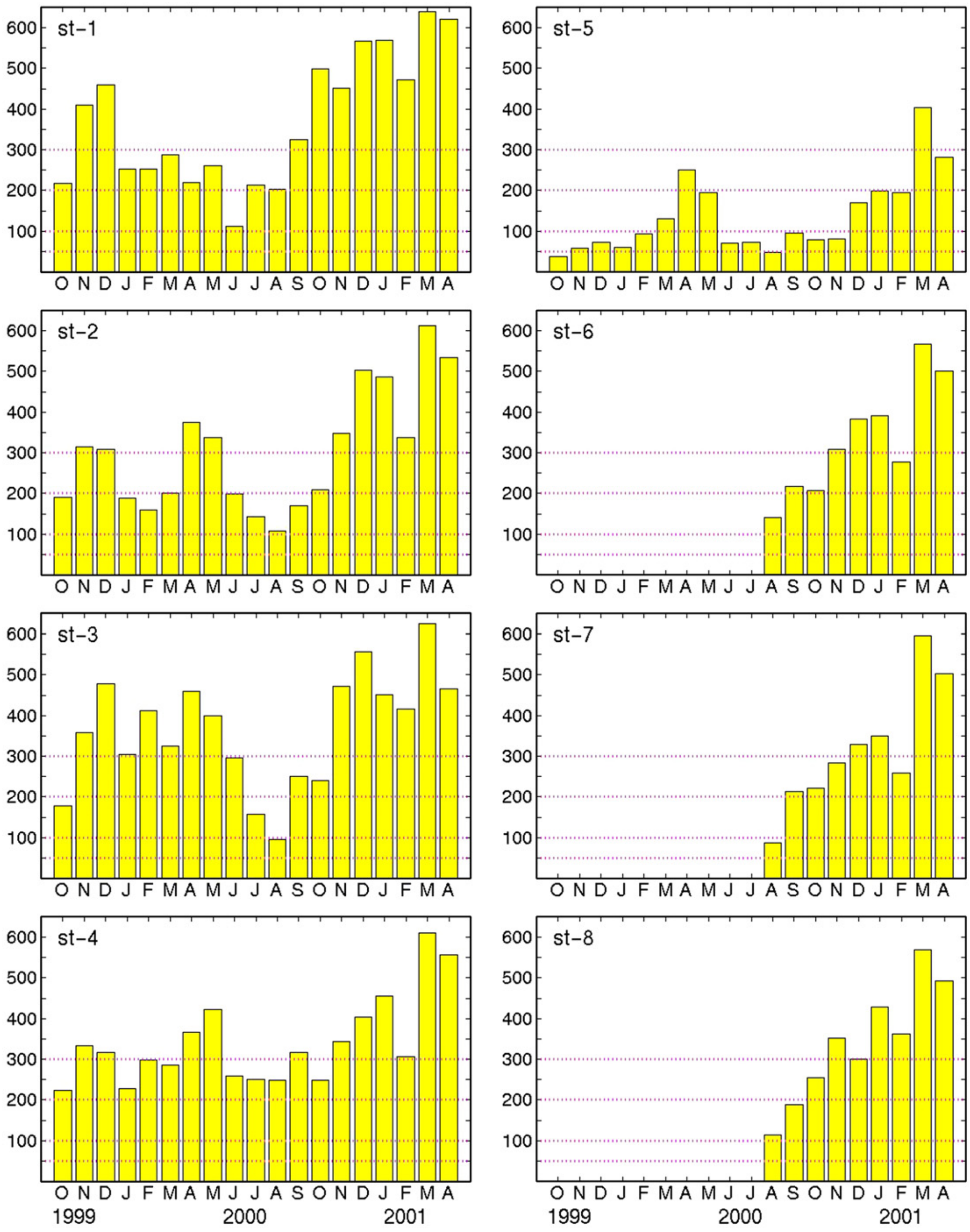

Fig. 4. Monthly mean API of TSP at St-1 to St-8.

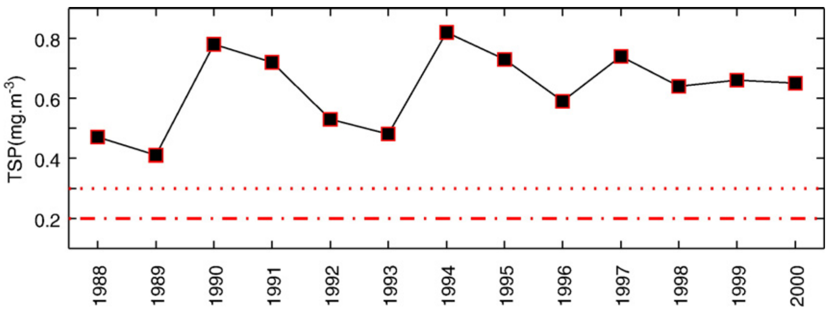

Fig. 5. Annual mean TSP concentration (mg m^{-3}) measured at the EPA-China station (103.631°E, 36.103°N), which is marked as the solid circle in Fig. 1b. The second-level criterion (0.2 mg m^{-3}) is represented by the horizontal dash-dotted line and the third-level criterion (0.3 mg m^{-3}) is represented by the horizontal dotted line.

standard: 0.3 mg m^{-3}. The second-level and third-level criteria of the annual mean of TSP are represented by dotted-dashed and dotted horizontal lines. The annual mean concentrations of TSP is higher than the third-level standard (0.3 mg m^{-3}) all the time from 1988 to 2000 and keeps quite steady with time (does not have an decreasing trend).

Table 9 shows the TSP observational days during the intensive observational period (October 1999 to April 2001).

Table 9
TSP observational days within each month from October 1999 to April 2001

Year	1999			2000												2001			
Month	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Obs Days	13	14	13	13	13	13	12	14	13	13	13	13	14	12	13	14	12	13	12

Table 10
TSP occurrence rate (%) of severe TSP alert, which is the ratio between the days with API of TSP greater than 200 and the total days of observation

Year	1999			2000												2001			
Month	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
St-1	54	79	100	46	62	69	33	71	0	38	38	85	93	83	92	100	92	100	92
St-2	39	57	69	23	15	23	75	79	38	15	8	31	50	67	92	93	75	100	83
St-3	38	86	100	69	92	46	75	93	85	8	0	46	57	100	100	86	92	100	83
St-4	38	71	92	38	69	54	67	93	54	54	62	62	57	75	85	93	83	100	83
St-5	0	7	0	0	15	23	42	43	8	8	0	8	7	8	31	21	25	69	50
St-6	–	–	–	–	–	–	–	–		–	8	54	43	83	77	71	67	100	83
St-7	–	–	–	–	–	–	–	–	–	–	0	46	50	58	77	79	50	100	83
St-8	–	–	–	–	–	–	–	–	–	–	8	38	50	75	62	86	58	92	83

The symbol '–' is referred to no-observational data.

Table 11
Occurrence rate (%) of different levels of TSP pollution

Season	Spring (331 observational days)	Summer (195 observational days)	Fall (381 observational days)	Winter (429 observational days)
API > 300	68	16	45	63
300 ≥ API > 200	11	11	15	13
200 ≥ API > 150	11	20	13	12
150 ≥ API > 100	5	26	14	7

Table 12
Occurrence rate (%) of different levels of PM_{10} pollution

Season	Spring (92 observational days)	Summer (88 observational days)	Fall (91 observational days)	Winter (90 observational days)
API > 300	25	1	8	32
300 ≥ API > 200	10	0	4	10
200 ≥ API > 150	22	7	22	25
150 ≥ API > 100	22	45	30	22

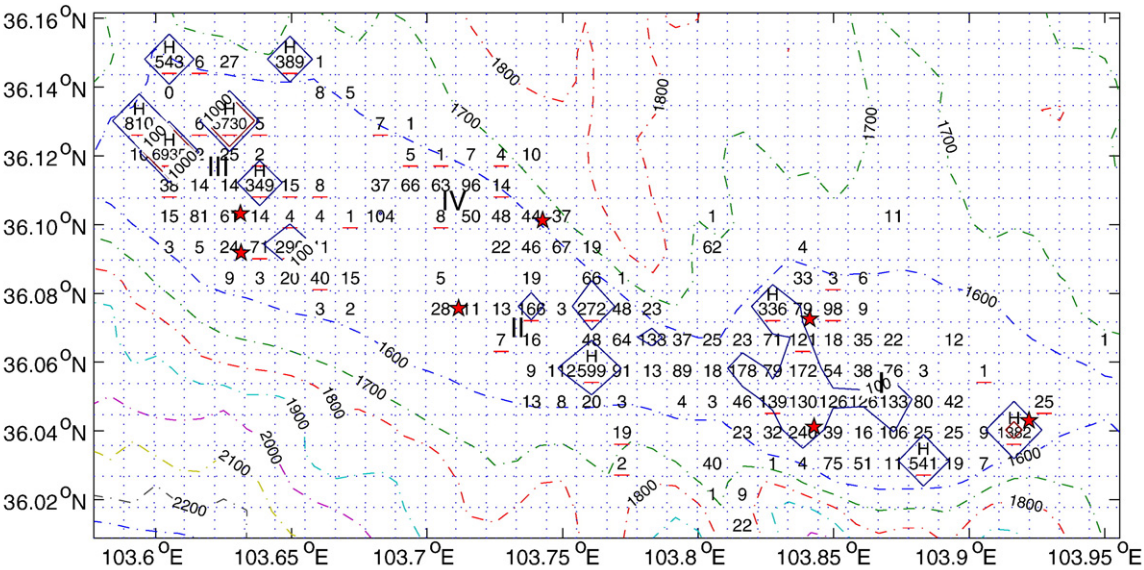

Fig. 6. Spatial distribution of annual particulate pollutant emission rate per square kilometer (unit: 0.1×10^4 kg km^{-2} yr^{-1}) in 2000. Here, the industrial sources are indicated with underlines; high-level sources are represented by the enclosed solid curves marked as 'H'. The dashed contours are topography (unit: m).

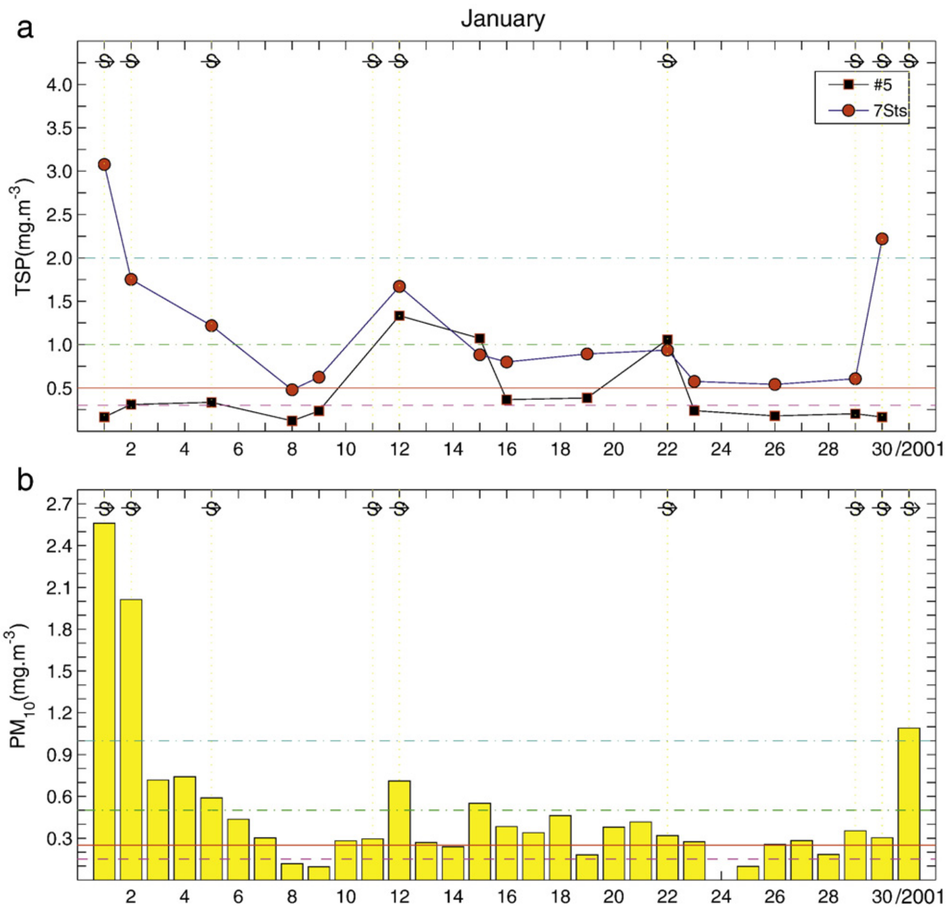

Fig. 7. Daily mean (a) TSP, (b) PM_{10} concentrations (dust storm represented by the symbol '') in January 2001, and (c) horizontal distribution of dust storms (solid dots) in January 2001.

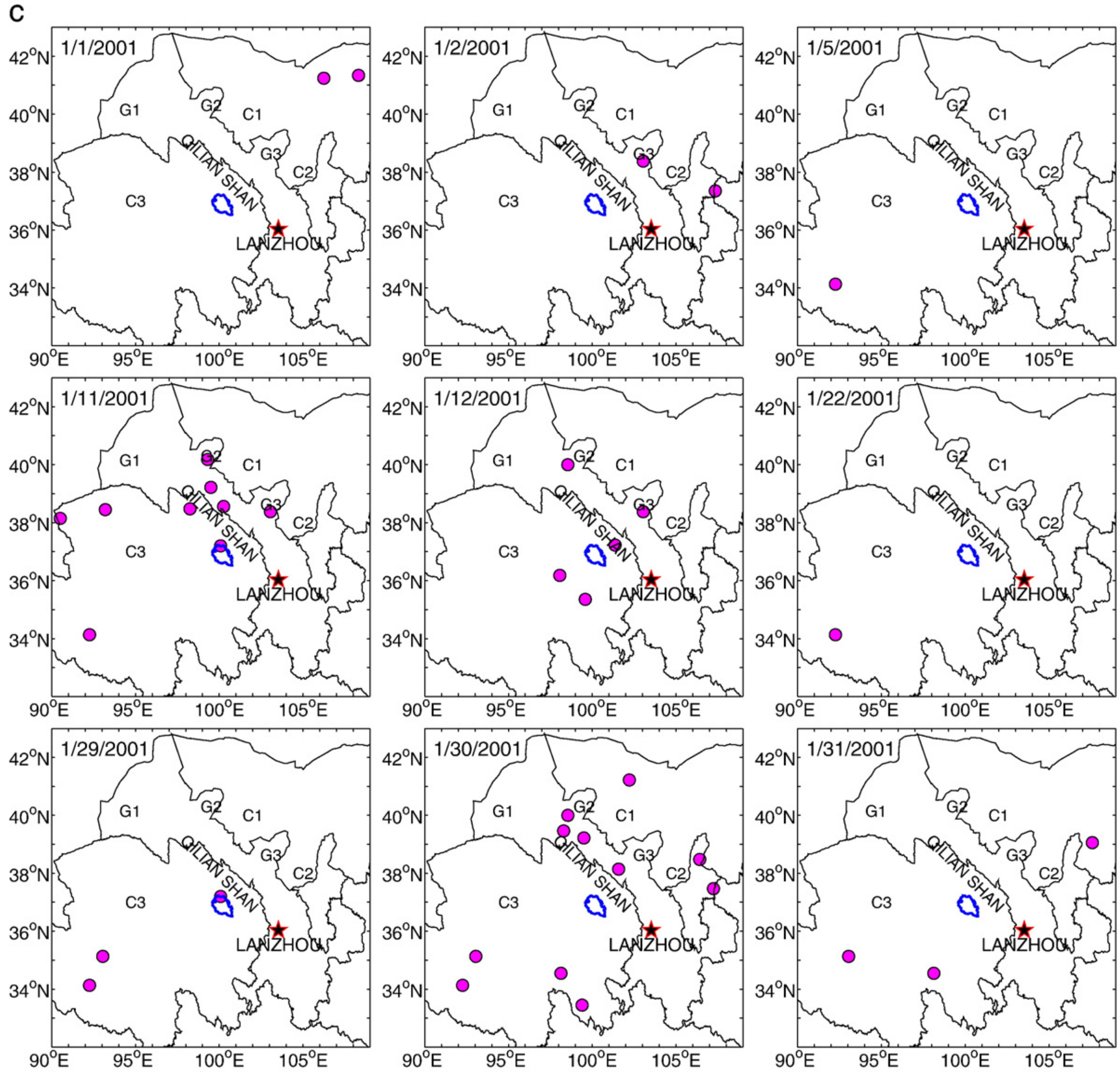

Fig. 7 (*continued*).

The occurrence rate of severe TSP alert is the ratio between the days with API of TSP greater than 200 and the total days of observation. Monthly mean API of TSP is larger than 200 almost all the time in winter and spring (Table 10) with some months even exceeding 300, such as in December 1999, December 2000 for St-3, in January, March 2001 for St-1, and in March 2001 for St-4 and St-7, where the API of TSP exceeds 300 all the time. According to Table 6, the TSP pollution in Lanzhou often reaches middle to high levels of pollution (categories IV and V).

The high-level TSP pollution (API > 300, category V) occurs frequently except summer (Table 11): 68% in the spring, 16% in the summer, 45% in the fall, and 63% in the winter. The occurrence rate of TSP pollution is usually smaller for mid and low levels than for the high level. For example, the low-level pollution (100 < API ≤ 150, category III) occurs at 5% in the spring, 26% in the summer, 14% in fall, and 7% in the winter.

Although the high-level PM_{10} pollution (API > 300, category V) occurs less frequently (Table 12) than that of TSP, it is still quite often in spring (25%) and winter (32%). The occurrence rate of PM_{10} pollution is usually larger for mid and low levels than for the high level. For example, the low-level pollution (100 < API ≤ 150, category III) occurs at 22% in spring, 45% in summer, 30% in fall, and 22% in winter.

5. Cause of particulate pollution

5.1. Local emission rate

Fig. 6 shows the spatial distribution of annual particulate pollutant emission rate per square kilometer (unit: 0.1×104 kg km^{-2} yr^{-1}) in 2000. Emission rate is the largest in District-III, mainly from industrial sources (indicated with underlines in Fig. 6),

Table 13
Dust storm statistics in Gansu Province from December 2000 to April 2001

Occurring time	Wind velocity (m.s−1)	Least visibility (m)	Scope of dust storms
12/31/2000– 1/1/2001	14–20, Max:23	<100	Dust storms in Jinta, Dingxing, Minqin, flying dust and flying ashes in other parts of Hexi and its eastern region
1/11/2001 –1/12/2001	12–17, Max: 22	<200	Dust storms in Jinta, Dingxing, Zhangye, Linze, Gaotai, Minqin, Yongchang, flying dust and flying ashes in other parts of Hexi and its eastern region
1/30/2001	11–19, Max: 22	<80	Dust storms in Jiuquan, Jinta, Gaotai, Yongchang, Guaizihu[1] Wudaoliang[2], Taole[3] etc, flying dust and flying ashes in other parts of Hexi and its eastern region
2/16/2001	10–15	250	Dust storms in Guannan[2], Maqu
2/23/2001	10–14	8	Dust storms in Dunhuang, Anxi
3/4/2001–3/5/2001	14–20, Max: 24	<100	Dust storms in Jiuquan, Dunhuang, Jinta, Dingxin, Minqin, Guaizihu[1], Bayanmaodao[1], Gangcha[2], Menyuan[2], Gonghe[2], Guannan[2] etc, flying dust and flying ashes in other parts of Hexi and its eastern region
3/13/2001	12–17	16	Dust storms in Guaizihu[1], Etuokeqi[1], Taole[3]
3/26/2001	11–15, Max: 19	<60	Dust storms in Dingxin,Wuwei, Jinchang, Shandan, Jintai, Guaizihu[1] etc, flying dust and flying ashes in other parts of Hexi and its eastern region
4/6/2001–4/8/2001	12–20, Max: 23	0	Dust storms in Dunhuang,Mazongshan, Dingxin, Jinta, Jiuquan, Zhangye, Linze, Gaotai, Shandan, Jinchang, Yongchang, Minqin, Wuwei, Gulang,Wushaoling, Jingyuan, Jingtai, Baiying, Yongdong, Lanzhou, Hezheng, Linxia, Huanxian, Pingliang, Huajialing, Dingxi, Xining[2], Wulan[2], Dulan[2],Wudaoliang[2] etc, flying dust and flying ashes in other parts of Gansu
4/12/2001	10–15, Max: 20	<10	Dust storms in Minqin, Wuwei, Jingtai, Wushaoling, flying dust and flying ashes in other parts of Hexi and its eastern region
4/19/2001	10–15	4	Dust storms in Dunhuang, Zhangye, Gaotai, Jintai
4/28/2001–4/29/2001	15–20, Max: 23	0	Dust storms in Dunhuang, Anxi, Yumen, Gaotai, Zhangye, Jinta, Jiuquan, Dingxing, Yongchang, Minqin, Jinchang, Baiyin, Jingtai, Yuzhong, Gaolan, Huining, Huajialing, flying dust and flying ashes in other parts of Hexi and its eastern region

The superscripts (1,2,3) represent the weather stations located in the surrounding provinces (Inner-Mongolia, Qinghai, Ningxia).

for instance, annual emission rates are 693.5×10^4 kg km^{-2} yr^{-1} from the Chemical Plant of Lanzhou and 573×10^4 kg km^{-2} yr^{-1} from the Electric Power Plant of Xigu (District-III). However, the total pollutant emission in Lanzhou is 4020.7×10^4 kg in 1999, and 3578.2×104 kg in 2000. From 1999 to 2000, it decreases 442.5×10^4 kg.

5.2. Dust storms

Although the local emission rate has been reduced, the TSP concentration is still high during the observational period. This is caused by the transport of the TSP due to dust storms. Recent studies indicate that dust storms originated in the East Asia not only influence air pollution in the origins and their neighboring regions (Uno et al., 2001; Murayama et al., 2001; Sun et al., 2001; Zhou et al., 2002), but also have a long-distance effect across Pacific by atmospheric circulation (Husar et al., 2001; Tratt et al., 2001; Sun et al., 2001; Laat et al., 2001; Clarke et al., 2001). The major sources of the dust storms are the Gobi desert in Mongolia and northern China and Taklimakan desert in western China (Sun et al., 2001). In April 1998, an Asian dust storm proceeded eastward with the west wind across Pacific Ocean and subsided to the surface along the mountain ranges between British Columbia and California (Husar et al., 2001; Tratt et al., 2001; Vaughan et al., 2001). Other reports indicated that there is a positive correlation between dust storm in Hexi Corridor and air pollution in Lanzhou (Wang et al., 1999; Ding et al., 2001). As one of the major cities in northwest China, and the capital of Gansu Province, Lanzhou suffers greatly from the dust storms (Wang et al., 1999; Ding et al., 2001). The particulate pollution in Lanzhou has been on the top among all cities in China.

With limited observations, several studies show the favorable meteorological condition for air pollution of Lanzhou such as inversion or stable stratification that suppresses atmospheric turbulence transfer (Hu and Zhang, 1999; Lu et al., 2001;Chen et al., 2001; Zhang, 2001). In addition, Shang et al. (2001) show significant correlation between static stability and concentrations of SO_2, CO, and NOx. Wang et al. (1999) and Ding et al. (2001) obtain positive correlation between dust storm occurrence in Hexi Corridor and the particulate pollution in Lanzhou.

As described in Section 4, TSP and PM_{10} are the most series pollutant in Lanzhou. Occurrence of high TSP and PM_{10} concentrations are associated with the propagation of dust storms. From Fig. 7 (January 2001) to Fig. 10 (April 2001), the daily TSP concentrations at the background station (St-5) and spatially averaged over seven (St-1 to St-4 and St-6 to St-8) city stations are illustrated in panel-a, and the daily PM_{10} concentration at St-E is shown in panel-b. On the two panels the dust storm is marked by the symbol ‘S’. Dust storms occur quite often in the vicinity of Lanzhou (Table 13): 9 days in January 2001, 3 days in February 2001, 9 days in March 2001, and 12 days in April 2001. For example, during the dust storm from December 31, 2000 to January 1, 2001, dusts float in the sky for 7 days (January 1–5, 2001) (Ding et

al., 2001), and causes high TSP and PM_{10} concentrations on January 1, 2001 (TSP: 3.08 mg m^{-3} and PM_{10}: 2.56 mg m^{-3}) and on January 2, 2001 (TSP: 1.75 mg m^{-3} and PM_{10}: 2.01 mg m^{-3}) as shown in Fig. 7.

Deserts and barren lands are widespread in the northwest of China and they are expanding attributing to underdeveloped methods of producing and management, and irrational utilization of resources. Aridness and desertization cause frequent dust storms (Dong et al., 1999; Wang and Cheng, 1999). Thick dots (listed in Figs. 7c–10c) represent the meteorological stations where the dust storms were reported. The dust storms that directly cause severe particulate pollution of Lanzhou are mainly generated in neighboring regions such as Hexi Corridor (Fig. 1a marked by G1, G2, G3), Badanjilin desert (100°–103°E, 39°–42°N, centered at C1), south of Tenggeli desert (103°–106°E, 37°–39°N, centered at C2), and Caidam desert (about 92°–98°E, 36°–38°N, centered at C3). These regions are enclosed as a ladder-shaped region (Fig. 1a).

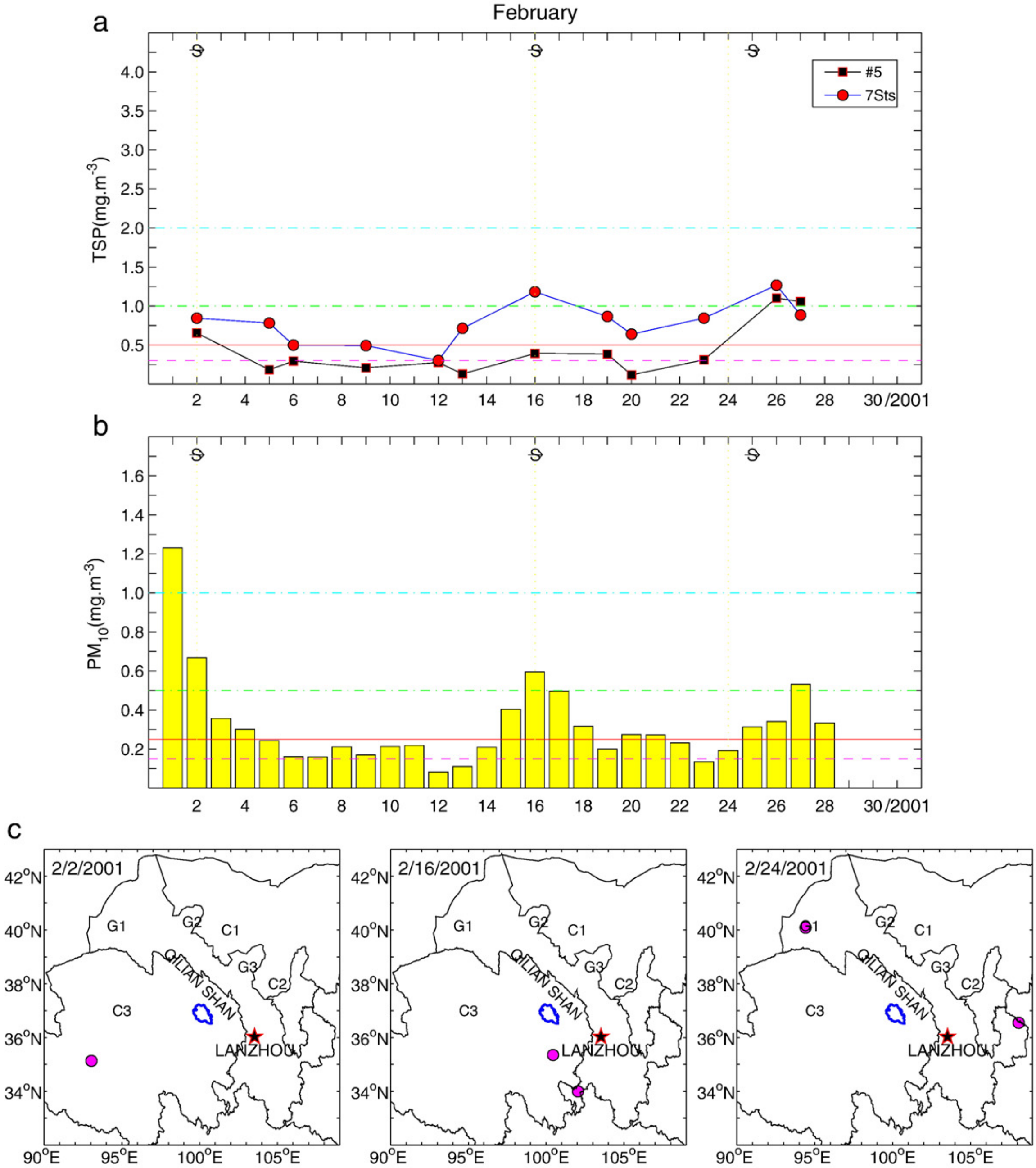

Fig. 8. Same as Fig. 7 except for February 2001.

When the air is dry, strong winds blowing over the deserts cause the dust storms and in turn brings high TSP and PM_{10} concentrations in Lanzhou.

6. Conclusions

(1) Special topographic features of Lanzhou metropolitan area (narrow and long valley) makes it vulnerable to the particulate pollution. This may be divided into local and remote effects. For local pollution sources, such topography causes weak winds and stable stratification. In the evening (occasionally even in the daytime) low-level inversion exists to inhibit turbulent diffusion and in turn to cause heavy particulate pollution. For remote sources (dust storms), the mountain-breeze helps the sinking of the particulate pollutants into the valley and causing severe problem. Data analysis shows that the dust storms occur quite often in the vicinity of Lanzhou and cause high TSP and PM_{10} concentrations in Lanzhou. The maximum TSP concentration was observed as 5.29 kg m^{-3} (March 2001).

(2) Observational studies show heavy TSP pollution in Lanzhou with 2–10 times greater than the third-level standard in winter and spring. March 2001 is the most severely polluted month with API > 500 all the time. The high-level TSP pollution (API > 300, category V) occurs frequently with 68% in spring, 16% in summer, 45% in fall, and 63% in winter.

(3) The PM_{10} pollution is also quite high in Lanzhou with the high-level pollution (API > 300, category V) occurring quite often in spring (25%) and winter (32%). The occurrence rate of PM_{10} pollution is usually larger for mid and low levels than for the high level. For example, the low-level pollution ($100 < API \le 150$, category III) occurs at 22% in spring, 45% in summer, 30% in fall, and 22% in winter.

(4) Reduction of the TSP and PM_{10} concentrations is an urgent issue for air quality control in Lanzhou and related to the reduction of dust storms in the vicinity. This may be achieved by the improvement of the land surface characteristics such as long term forestation and vegetation.

Acknowledgments

This work was jointly supported by the National Natural Science Foundation of China Major Programs No. 40305020, and the Naval Postgraduate School of USA. The authors wish to thank Prof. J. Wang for the invaluable comments. The data for this study are provided by the program entitled "Air Pollution and Control in Lanzhou" jointly sponsored by the local government of Gansu Province and the Chinese Academy of Science.

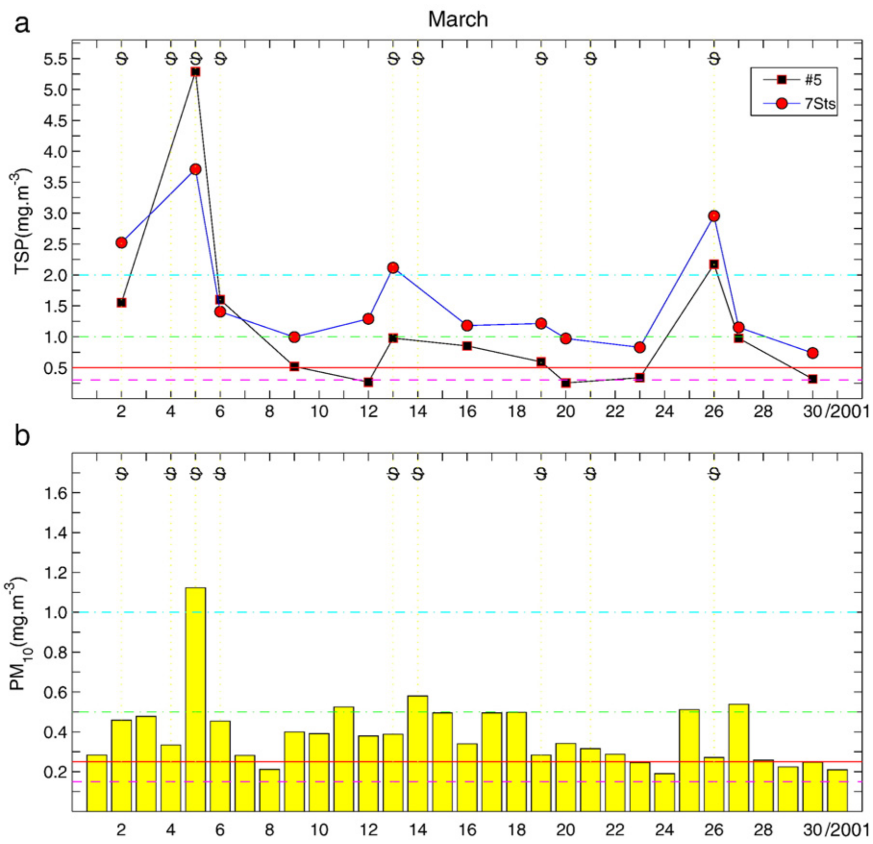

Fig. 9. Same as Fig. 7 except for March 2001.

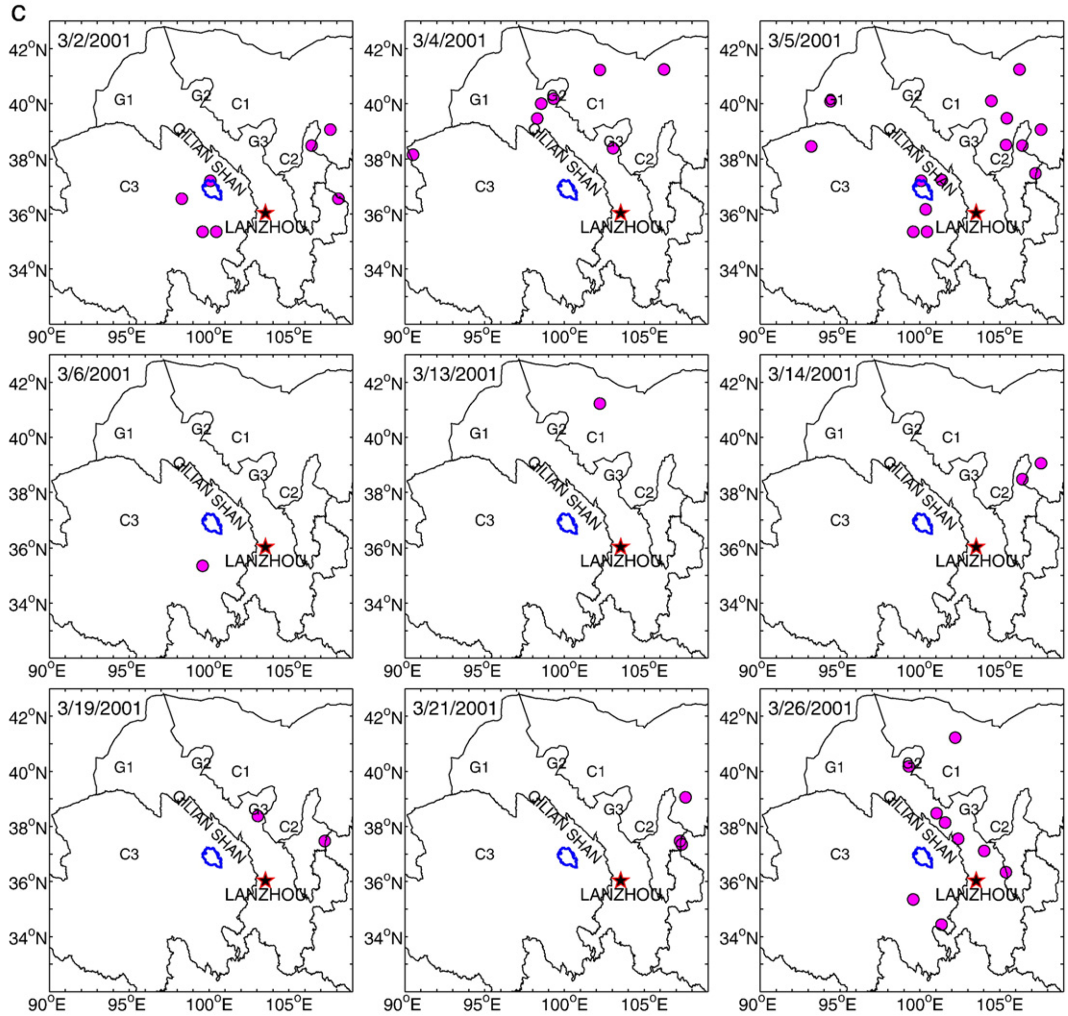

Fig. 9 (*continued*).

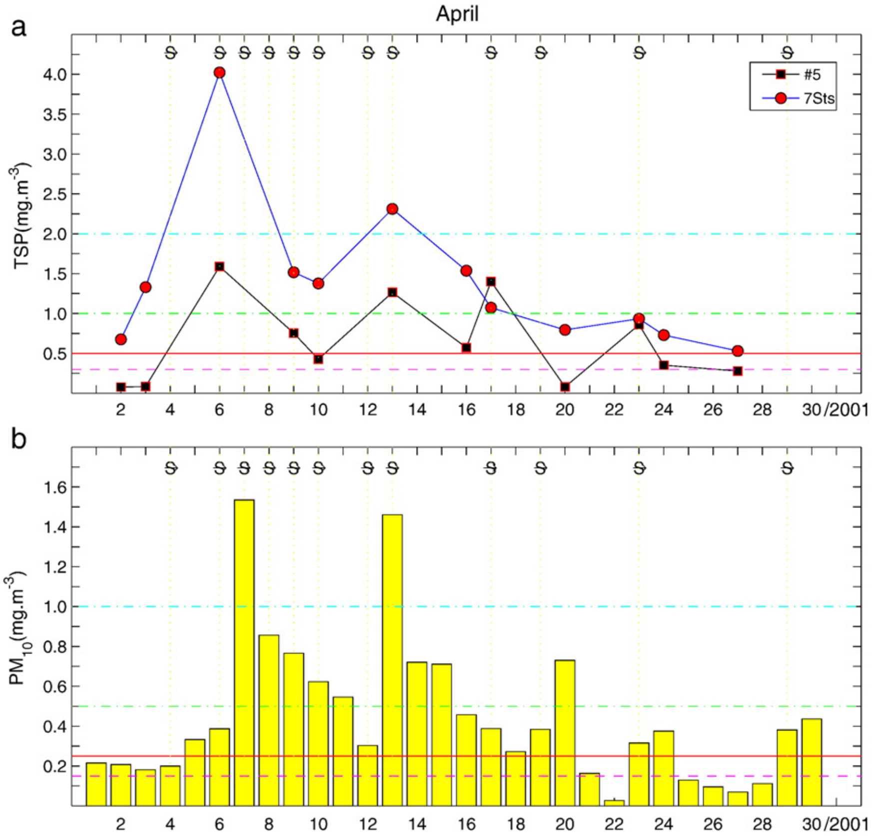

Fig. 10. Same as Fig. 7 except for April 2001.

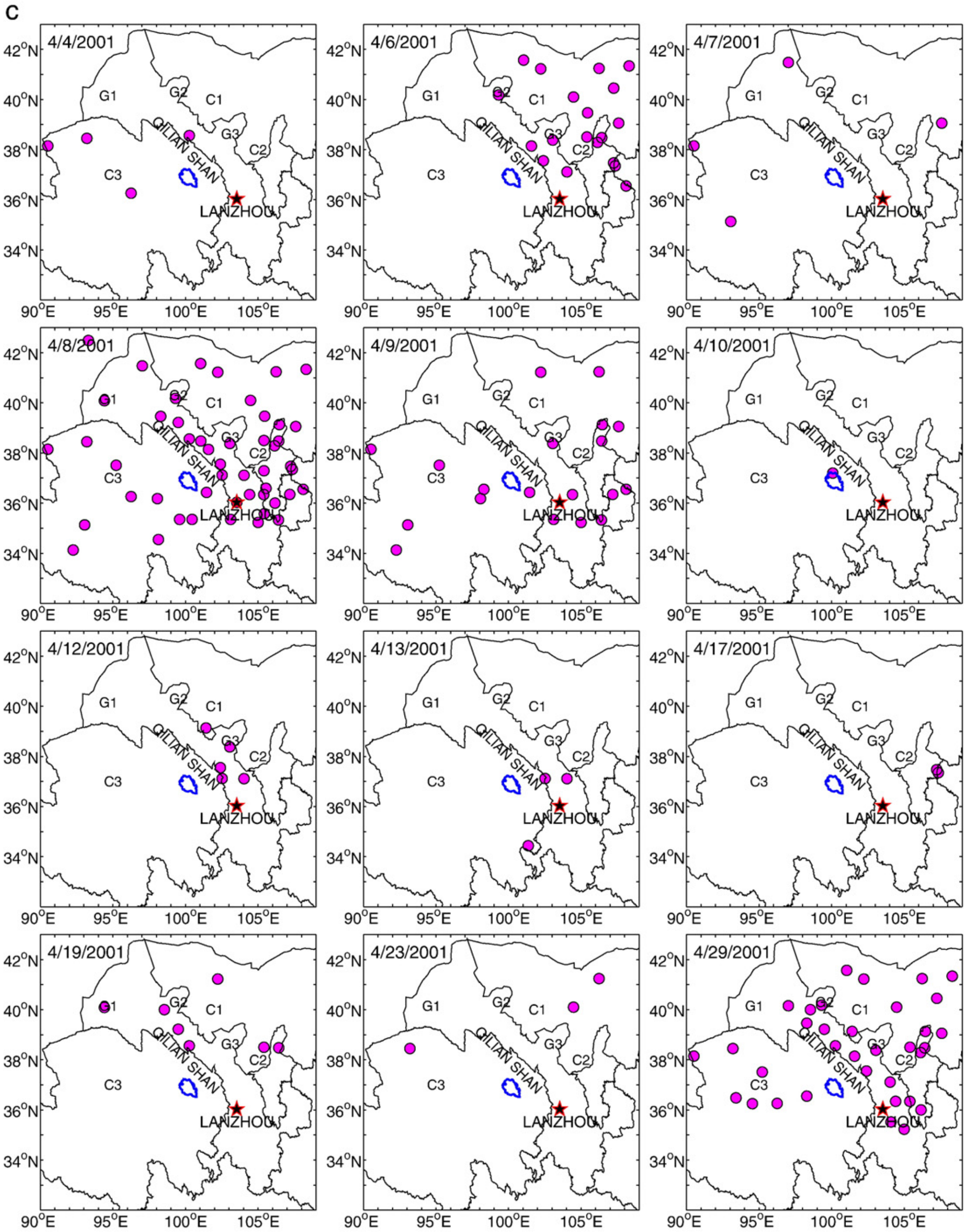

Fig. 10 (*continued*).

References

Chen YC, An XQ, Lu SH. Precautionary strategy of the influence of afforestation on air pollution in Lanzhou. Plateau Meteorol 2001;20:126–32 (Suppl.) [in Chinese with English abstract].

Chu PC, Chen Y, Lu SH. Afforestation for valley urban air quality improvement. Proc. Fifth Symposium on Urban Environment, Amer. Meteorol. Soc., Vancouver, August 23–27, 7. 2004 [in CD-Rom].

Chu PC, Chen Y, Lu SH. Afforestation for reduction of NOx concentration in Lanzhou China. Environmental International 2008;34:688–97 (this issue). doi:10.1016/j.envint.2007.12.014.

Clarke AD, Collins WG, Rasch PJ, Kapustin VN, Moore K, Howell S, et al. Dust and pollution transport on global scales: aerosol measurements and model predictions. J Geophys Res 2001;106(D23):32555–69 (2000JD900842).

Ding RQ, Yang DB, Wang SG, Shang KZ, Li JH. The effect of sandstorm on air pollution over Lanzhou city. Plateau Meteorol 2001;20:104–9 (Suppl.) [in Chinese with English abstract].

Dong GR, Wu B, Ci LJ, Zhou HS, Lu Q, Luo B. Present situation, cause and control way of desertification in China. J Desert Res 1999;19(4):318–32 [in Chinese with English abstract].

Duce RA, Unni CK, Ray BJ, Prospero JM, Merrill JT. Long-range atmospheric transport of soil dust storm from Asia to the tropical North Pacific: Temporal variability. Science 1980;209:1522–4.

Husar RB, Tratt DM, Schichtel BA, Falke SR, Li F, Jaffe D, et al. Asian dust events of April 1998. J. Geophys. Res 2001;106(D16):18317–30 (2000JD900788).

Hu YQ, Zhang Q. Atmosphere pollution mechanism along with prevention and cure countermeasure of the Lanzhou hollow basin. China Environ Sci 1999;19(2):119–22 [in Chinese with English abstract].

Laat ATJ, Lelieveld J, Roelofs GJ, Dickerson RR, Lobert JM. Source analysis of carbon monoxide pollution during INDOEX 1999. J Geophys Res 2001;106 (D22):28481–95 (2000JD900769).

Lu SH, Chen YC, An XQ. Numerical simulation of local circumfluence and inversion of Lanzhou. Plateau Meteorol 2001;20(Suppl.):1–7 [in Chinese with English abstract].

Murayama T, Sugimoto N, Uno I, Kinoshita K, Aoki K, Hagiwara N, et al. Ground-based network observation of Asian dust events of April 1998 in east Asia. J Geophys Res 2001;106(D16):18345–59 (2000JD900554).

Prospero JM, Ginoux P, Torres O, Nicholson SE, Gill TE. Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Rev Geophys 2002;40(1):1002. doi:10.1029/2000RG000095.

Shang KZ, Da CY, Fu YZ, Wang SG, Yang DB. The stable energy in Lanzhou city and the relations between air pollution and it. Plateau Meteorol 2001;20(1):76–81 [in Chinese with English abstract].

Sun JM, Zhang MY, Liu TS. Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960–1999: relations to source area and climate. J Geophys Res 2001;106(D10):10325–33 (2000JD900665).

Tratt DM, Frouin RJ, Westphal DL. April 1998 Asian dust event: a southern California perspective. J Geophys Res 2001;106(D16):18371–9 (2000JD900758).

Uno I, Amano H, Emori S, Kinoshita K, Matsui I, Sugimoto N. Trans-Pacific yellow sand transport observed in April 1998: a numerical simulation. J Geophys Res 2001;106(D16):18331–44 (2000JD900748), 2001.

Vaughan JK, Claiborn C, Finn D. April 1998 Asian dust event over the Columbia Plateau. J Geophys Res 2001;106(D16):18381–402 (2000JD900751).

Wang GX, Cheng GD. Land desertification status and developing trend in the Heihe River basin. J Desert Res 1999;19(4):368–74 [in Chinese with English abstract].

Wang SG, Yang M, Qi B, Xin CL, Yang MF. Influence of sand-dust storms occurring over the Gansu Hexi District on the air pollution in Lanzhou City. J Desert Res 1999;19(4):354–8 [in Chinese with English abstract].

Wang SG, Wang JY, Zhou ZJ, Shang KZ, Yang DB, Zhao ZS. Regional characteristics of dust events in China. J Geogr Sci 2003;13:35–44.

Zhang Q. The influence of terrain and inversion layer on pollutant transfer over Lanzhou city. China Environ Sci 2001;21(3):230–4 [in Chinese with English abstract].

Zhou J, Yu GM, Jin CJ, Qi F, Liu D, Hu HL, et al. Lidar observations of Asian dust over Hefei, China, in spring 2000. J Geophys Res 2002;107(15): 4252. doi:10.1029/2001JD000802.